isospin

n $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ ✓

Mass $m = 1.0086649158 \pm 0.0000000006$ u
Mass $m = 939.56533 \pm 0.00004$ MeV [a]
$m_n - m_p = 1.2933318 \pm 0.0000005$ MeV
$= 0.0013884489 \pm 0.0000000006$ u
Mean life $\tau = 885.7 \pm 0.8$ s
$c\tau = 2.655 \times 10^8$ km
Magnetic moment $\mu = -1.9130427 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 0.63 \times 10^{-25}$ e cm, CL = 90%
Mean-square charge radius $\langle r_n^2 \rangle = -0.1161 \pm 0.0022$ fm^2 (S = 1.3)
Electric polarizability $\alpha = (9.8^{+1.9}_{-2.3}) \times 10^{-4}$ fm^3 (S = 1.1)
Charge $q = (-0.4 \pm 1.1) \times 10^{-21}$ e

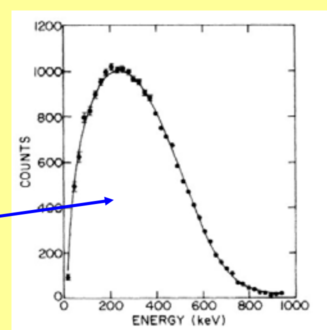
Lifetime: 885.7 ± 0.8 sec (world average)

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Neutron beta decay:

Reaction: $n \rightarrow p + \boxed{e^- + \bar{\nu}_e}$

light particles or "leptons", produced in association.



Neutrino presence is crucial to explain the shape of the electron energy spectrum:

(otherwise, the electrons would be monoenergetic – 2 body final state!)

- "Neutrino" or "little neutral one" postulated in 1931 by Pauli ($q = 0$, $m_\nu = 0$, $s = \frac{1}{2}$)
- Only associated with the weak interaction – very difficult to detect
- First detected by Reines & Cowan, 1959 → Nobel prize 1995

Related processes: 3

1) $p \rightarrow n + e^{+} + \nu_e$ — "β+ decay" in a nucleus, where energetically favourable, eg $^{25}Al \rightarrow {}^{25}Mg$ decay

2) $p + e^{-} \rightarrow n + \nu_e$ — "Electron capture" or EC decay in a nucleus; inner shell **atomic** electron is captured.

3) $\bar{\nu}_e + p \rightarrow n + e^{+}$ — "Antineutrino capture", used by Reines & Cowan to detect the antineutrino.

… **and many more!!!**

Notice: the electron and anti-neutrino appear together;
the positron and neutrino appear together….

This suggests a new conserved quantity called "**lepton number**", **L_e** : *(F&H ch. 7)*

$$\begin{pmatrix} e^{-} \\ \nu_e \end{pmatrix} \text{ have } L_e = +1; \qquad \begin{pmatrix} e^{+} \\ \bar{\nu}_e \end{pmatrix} \text{ have } L_e = -1$$

Empirical conservation law: L_e = constant $\rightarrow$ ν_e and $\bar{\nu}_e$ are distinct !!

Detection of anti-neutrinos: 4

$$\bar{\nu}_e + p \rightarrow n + e^{+}$$

"Antineutrino capture" reaction used by Reines & Cowan to detect the antineutrino.

Nobel-prize winning experiment:

http://www.nobel.se/physics/laureates/1995/illpres/neutrino.html

Detection of the Free Antineutrino*

F. Reines,† C. L. Cowan, Jr.,‡ F. B. Harrison, A. D. McGuire, and H. W. Kruse
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^{+})n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

(Physical Review 117, p. 159, 1960)

Reines & Cowan Experiment (1953): 5

$$\bar{\nu}_e + p \rightarrow n + e^+$$

intense beam from a nuclear reactor

protons in large water tanks

slow down by scattering in the water; detect by capture in dissolved Cd salt

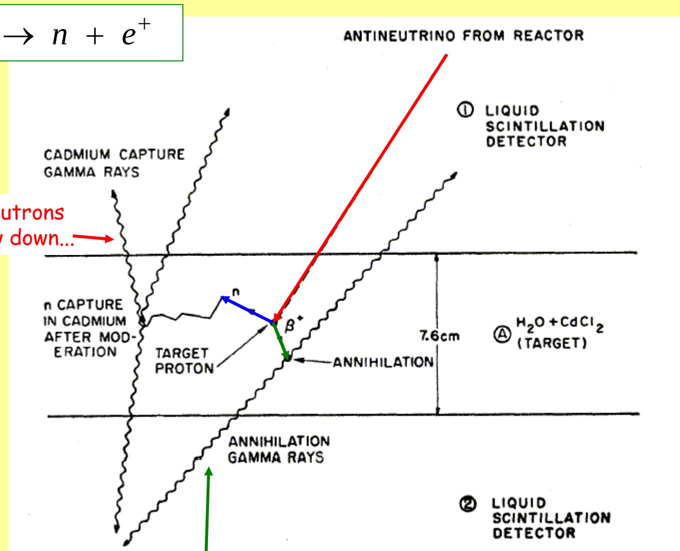
detect via gamma rays from annihilation with e-

- Very low rate experiment: > 10^{13} incident antineutrinos/sec but only 3 events/hr!
  → 5 months of data taking!
- No computer data acquisition! For each event, an automatically-triggered camera system took a photograph of analog oscilloscope traces!
- "Delayed coincidence" detection of both neutron and positron suppressed background
- Auxiliary measurements to determine detection efficiencies, etc.
- Absolute cross section measured was 1 x 10^{-43} cm^2 (10^{-19} b), in agreement with theory!!

Schematic of the experiment: 6

$$\bar{\nu}_e + p \rightarrow n + e^+$$

delayed: neutrons have to slow down...



positron annihilation (instantaneous): $e^+ + e^- \rightarrow 2\gamma$ (511 keV)

2 water tanks, sandwiched between 3 scintillation counters to detect γ's

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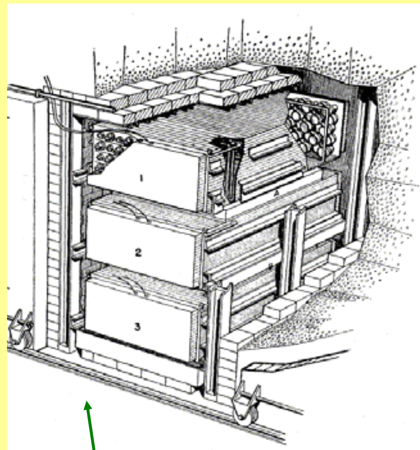
EQUIPMENT

A consideration of the cross section for reaction (1) averaged over the fission antineutrino spectrum ($\sim 10^{-43}$ cm^2) and the available $\bar{\nu}$ flux ($\sim 10^{13}$ cm^{-2} sec^{-1}) made it apparent that large numbers of target protons would be required. These were provided by two plastic target tanks containing 200 liters of water each, shaped as slabs 7.6 cm deep and 132 cm by 183 cm in lateral dimensions. Each water tank was sandwiched between two of the three large liquid scintillation detectors (Fig. 2). The thickness of the water tanks was limited by the absorption of the 0.5-Mev positron-annihilation radiation produced in the antineutrino reaction. The array of tanks formed two "triads" with one detector tank in common. The 58-cm depth of the scintillation detectors was chosen so as to absorb the cadmium-capture gammas with the maximum efficiency attainable in the space available for the system. Consideration of light-collection efficiency and the energy resolution required of the system resulted in the use of an extremely transparent liquid scintillation solution containing 3 grams/liter of terphenyl and 0.3 gram/liter of POPOP in highly purified triethylbenzene.[3]

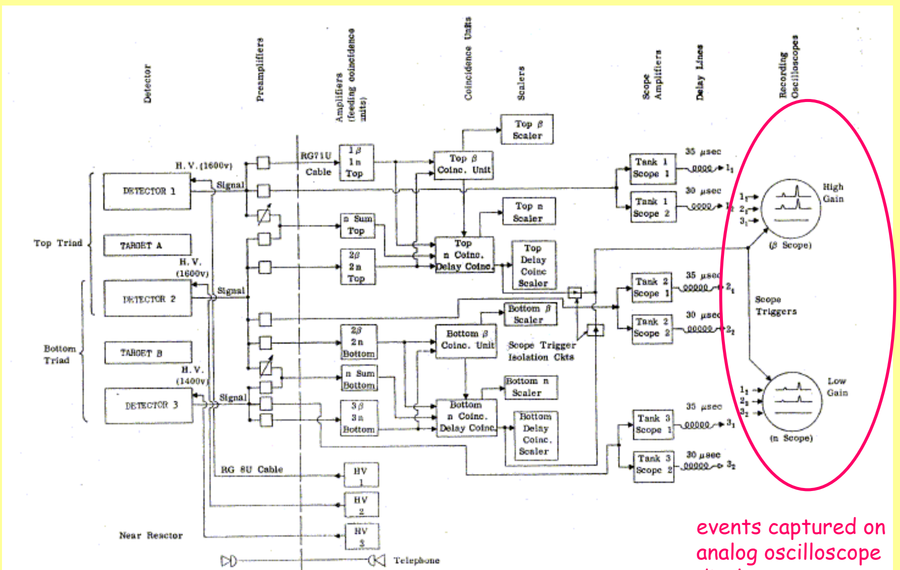
$$\overline{\nu}_e + p \rightarrow n + e^+$$



vertical height ~ 2 m; surrounded in Pb shielding to reduce γ background...

No computers! electronic coincidence pulses for e+ and n-capture γ's....

8

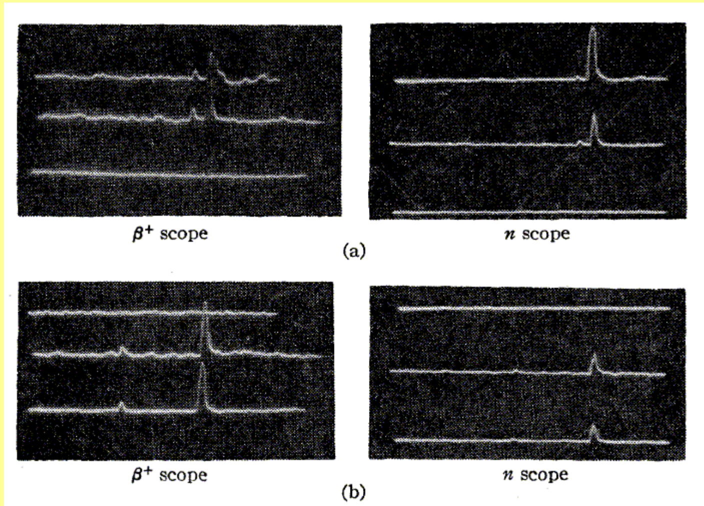


events captured on analog oscilloscope displays....

FIG. 4. Schematic diagram of detector and associated electronics.

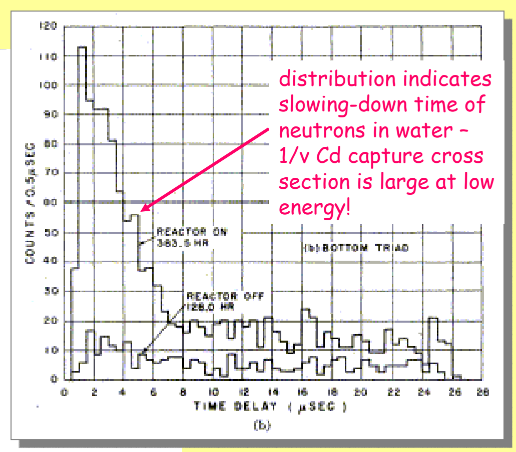
Raw data: oscilloscope photographs!

scintillation light from e+ annihilation first, neutron capture later (3 – 10 μs)



Data: coincidence event rate as a function of time delay

Reines and Cowan beside one of their neutrino detectors. The experiment was jokingly called "Project Poltergeist" since the neutrino was considered to be as elusive as a ghost.

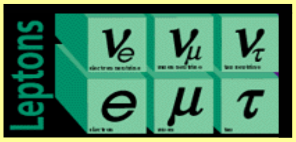


distribution indicates slowing-down time of neutrons in water – 1/v Cd capture cross section is large at low energy!

$$\boxed{\sigma \;=\; 1.2\,^{+0.7}_{-0.4} \times 10^{-43}\ \text{cm}^2}$$

Bottom line: first direct demonstration of the existence of antineutrinos!

More on lepton number:



$L_e \quad L_\mu \quad L_\tau$

There are actually three "generations" of leptons that we know about (in order of increasing mass: e, μ, τ) and each one has its own distinct associated neutrino type with a separately conserved lepton number....

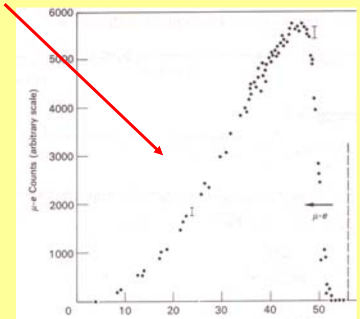
Example: muon decay: two distinct neutrinos are emitted, as proved by the spectrum shape

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

PDG listing: **μ^- DECAY MODES**

μ^+ modes are charge conjugates of the modes below.

Mode			Fraction (Γ_i/Γ)
$e^- \bar{\nu}_e \nu_\mu$			$\approx 100\%$
$e^- \bar{\nu}_e \nu_\mu \gamma$		[a]	(1.4 ± 0.4) %
$e^- \bar{\nu}_e \nu_\mu e^+ e^-$		[b]	$(3.4\pm0.4) \times 10^{-5}$
Lepton Family number (*LF*) violating modes			
$e^- \nu_e \bar{\nu}_\mu$	*LF*	[c]	< 1.2 %
$e^- \gamma$	*LF*		$< 1.2 \times 10^{-11}$
$e^- e^+ e^-$	*LF*		$< 1.0 \times 10^{-12}$
$e^- 2\gamma$	*LF*		$< 7.2 \times 10^{-11}$



see F&H sec 11.5